Partonic flow and ϕ-meson production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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We present first measurements of the ϕ-meson elliptic flow ($v_2(p_T)$) and high statistics p_T distributions for different centralities from $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC. In minimum bias collisions the v_2 of the ϕ meson is consistent with the trend observed for mesons. The ratio of the yields of the Ω to those of the ϕ as a function of transverse momentum is consistent with a model based on the recombination of thermal s quarks up to $p_T \sim 4$ GeV/c, but disagrees at higher momenta. The nuclear modification factor (R_{CP}) of ϕ follows the trend observed in the K^0_S mesons rather than in Λ baryons, supporting baryon-meson scaling. Since ϕ-mesons are made via coalescence of seemingly thermalized s quarks in central Au+Au collisions, the observations imply hot and dense matter with partonic collectivity has been formed at RHIC.

PACS numbers:

The primary aim of ultra-relativistic heavy-ion collisions is to produce and study a state of high-density nuclear matter called the Quark-Gluon Plasma (QGP), the existence of which is supported by lattice QCD calculations [1, 2, 3]. In the search for this new form of matter, penetrating probes are essential in order to gain information from the earliest stage of the collisions. Phenomenological analysis [4] has suggested a relatively small hadronic interaction cross section for ϕ-mesons although discussions about the $\phi-$proton interaction cross section are yet to be conclusive [5, 6]. Therefore ϕ-mesons from high-energy nuclear collisions are expected to provide information about the early partonic stages of the system's evolution since they should remain mostly unaffected by hadronic interactions. This is further supported by recent measurements [7] which have ruled out the idea of ϕ-meson production by kaon coalescence.

Elliptic flow, v_2, is an observable which is thought to reflect conditions from the early stage of the collision [8, 9]. In non-central heavy-ion collisions, the initial spatial anisotropy of the overlap region of the colliding nuclei is transformed into an anisotropy in momentum space through interactions between the particles. Systematic measurements of the v_2 for the strange hadrons K^0_S, Λ, Ξ and Ω suggest that collectivity is developed at the partonic stage at RHIC [10, 11]. The evidence for partonic collectivity, one of the conditions for QGP formation, will be further strengthened if it can be shown that ϕ-mesons flow like the other mesons.

A mass ordering predicted by hydrodynamics [12, 13, 14] for $v_2(p_T)$ of identified particles has been observed for $p_T \leq 2$ GeV/c. At intermediate transverse momentum, $2 \leq p_T \leq 5$ GeV/c, a separation of baryons and mesons has been observed in measurements of both v_2 and the nuclear modification factor, R_{CP} [11, 15, 16]. These results are consistent with calculations from quark recombination models [17, 18, 19, 20] implying the deconfinement of the system prior to hadronization. The ϕ is a vector meson, comparable in mass to the proton and Λ baryons with a relatively long lifetime. Its v_2 and R_{CP} will provide a critical test of the assumed underlying dynamics. In addition, as argued in [21], the ratio of the Ω-baryon over ϕ-meson yields can be used to test the nature of light-quark thermalization in the medium. The model predicts that the ratio of the Ω to ϕ yields will rise monotonically.

The results presented in this paper were obtained with the STAR detector [22] at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. The detector components used in this analysis were the Time Projection Chamber (TPC), and trigger detectors, namely the zero degree calorimeters. Central collisions were selected using the Central Trigger Barrel. The collision centrality was determined by the charged hadron multiplicity within pseudo-rapidity $|\eta| < 0.5$.

High-statistics Au+Au data were taken in the 2004 run at $\sqrt{s_{NN}} = 200$ GeV. The minimum bias dataset used in this analysis consisted of ~13.5 million events and the central-triggered dataset comprised about 10 million events. Events were required to have a primary vertex z position (where z is the direction of the beam axis) within 30 cm of the center of the TPC. Events from the minimum bias dataset were divided into 8 centrality bins: 0-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, and 70-80% of the measured cross-section. The central-triggered dataset was used to extract the 0-5% and 0-12% data.

The ϕ yield in each p_T bin was extracted from the invariant mass (m_{inv}) distributions of $K^+ + K^-$ candidates after subtraction of combinatorial background estimated using event mixing [7]. The kaons were identified through their dE/dx energy loss in the STAR TPC [22]. Including the detector resolution, the values of the reconstructed ϕ mass and width are consistent with the PDG values [23]. The relative systematic uncertainty due to the dE/dx cut was estimated to be $\sim 8\%$ by using different cuts and comparing the yields after a particle identification efficiency correction. Uncertainty in the residual background shape of the m_{inv} distributions resulted in a contribution of about 4.5% to the errors on the final yields.

The ϕ-meson v_2 results were obtained using the v_2 vs. m_{inv} method described in ref. [24]. The method involves calculating the v_2 of the same-event distribution as a function of m_{inv} and then fitting the resulting $v_2(m_{inv})$ distribution using:

$$v_2(m_{inv}) = v_{2S}\alpha(m_{inv}) + v_{2B}(m_{inv})[1-\alpha(m_{inv})] \quad (1)$$

where $v_{2S} \equiv v_{2\phi}$ is the signal v_2 and v_{2B} is the background v_2. $\alpha(m_{inv}) = S/(S+B)$ is the ratio of the signal over the sum of the signal plus background of the m_{inv} distributions. It was extracted from fits (Breit-Wigner plus a linear function) to the ϕ mass-peak for each p_T bin. For each p_T bin, the $v_2(m_{inv})$ was fitted using Eq. 1 in order to extract the fitting parameter v_{2S} and v_{2B} was parameterized using a linear or quadratic function in m_{inv}. These results are consistent with results using an established method [25] where the ϕ-meson yield is plotted as a function of the difference between its azimuthal angle and the estimated reaction plane angle, $(\phi - \Psi)$. The values of v_2 are extracted from the fitting to the function $dN/d\phi = P_0(1 + 2v_2\cos(2(\phi - \Psi)))$.

In the top panel of Fig. 1 we present the first measurement of the differential elliptic flow, $v_2(p_T)$, of the ϕ-meson from Au+Au collisions for four centrality bins. In this and the following figures, the vertical error bars on the ϕ data points indicate the statistical errors while the shaded bands indicate the extent of the systematic uncertainties. The systematic errors vary from point to point including uncertainties in extracting the signal for obtaining $\alpha(m_{inv})$ and differences in the reaction plane resolution determination. For minimum bias collisions, an additional contribution to account for the different methods of extracting the $v_2(p_T)$ values is also included in the systematic error. Non-flow effects [26, 27] are not

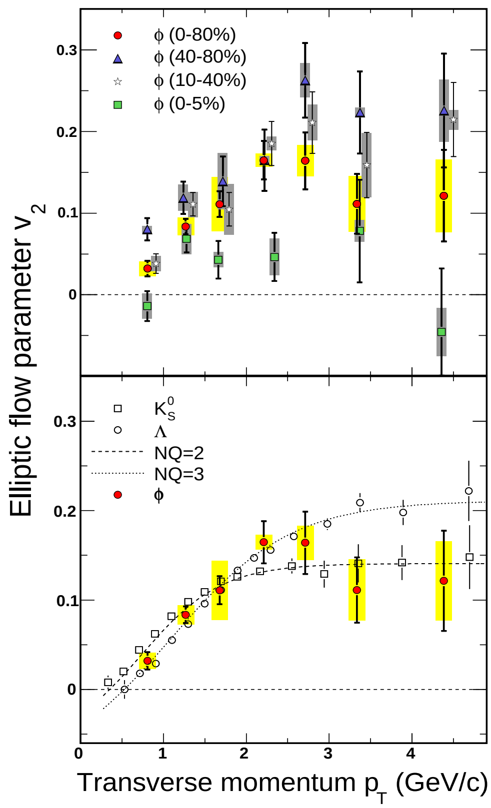

FIG. 1: (color online) **Top panel:** The elliptic flow, $v_2(p_T)$, for the ϕ-meson as a function of centrality. The vertical error bars represent the statistical errors while the shaded bands represent the systematic uncertainties. For clarity, data points are shifted slightly. **Bottom panel:** Minimum bias $v_2(p_T)$ for the ϕ-meson compared to results for Λ and K^0_S [11]. The dashed and dotted lines represent parameterizations inspired by number-of-quark scaling ideas from ref. [28] for NQ=2 and NQ=3 respectively.

included in the systematic error. As expected, $v_2(p_T)$ increases with increasing eccentricity (decreasing centrality) of the initial overlap region. This trend is also illustrated in Table I which presents the p_T-integrated values of ϕ-meson elliptic flow, $\langle v_2 \rangle$, calculated by convoluting the $v_2(p_T)$ with the respective p_T spectrum for three centrality bins. It should be noted that the centrality dependence of the $\langle v_2 \rangle$ of ϕ-mesons is consistent with that of charged hadrons [27].

TABLE I: Integrated elliptic flow, $\langle v_2 \rangle$, for the ϕ-meson for three centrality bins.

Centrality (%)	$\langle v_2 \rangle$ (%)
40 – 80	$8.5 \pm^{1.1(stat)}_{0.2(sys)}$
10 – 40	$6.6 \pm^{0.8(stat)}_{0.2(sys)}$
0 – 5	$2.1 \pm^{1.2(stat)}_{0.5(sys)}$

The lower panel of Fig. 1 shows the minimum bias (0-80%) result compared to parameterizations for number-of-quark scaling for mesons (NQ=2) and baryons (NQ=3) whose free parameters have been fixed by fitting to the Λ and K^0_S results simultaneously [28]. In this case, for $p_T < 2$ GeV/c, the ϕ v_2 follows a mass-ordered hierarchy where the values of v_2, within errors, fall between those of the heavier Λ (open circles) and lighter K^0_S (open-squares). However, at intermediate p_T, between 2-5 GeV/c, the ϕ v_2 appears to follow the same trend as K^0_S. When we fit the $v_2(p_T)$ of ϕ-mesons with the quark number scaling ansatz [28], the resulting fit parameter NQ $= 2.3 \pm 0.4$. The fact that the ϕ $v_2(p_T)$ is the same as that of other mesons indicates that the heavier s quarks flow as strongly as the lighter u and d quarks. As previously mentioned, ϕ-mesons are not formed through kaon coalescence [7] and do not participate strongly in hadronic interactions. Therefore the results demonstrate partonic collectivity.

Figure 2 shows the p_T distributions of ϕ-mesons as a function of centrality. The central-triggered dataset was used to obtain the most central spectrum while the other distributions were obtained using the minimum bias dataset. The error bars shown in Fig. 2 are statistical only. In the figure, the errors are smaller than the size of the data points.

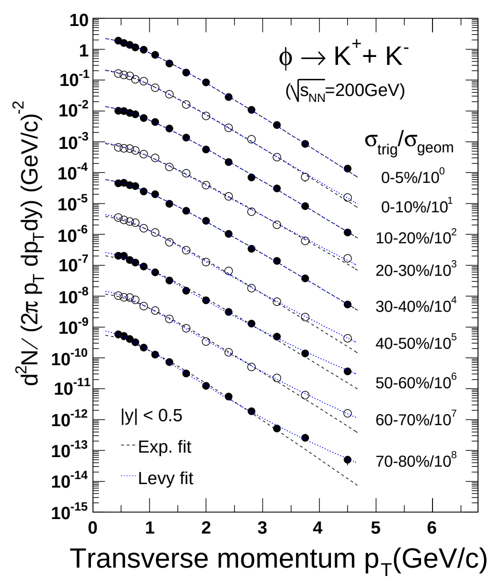

FIG. 2: (color online) Transverse momentum distributions of ϕ-mesons from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. For clarity, distributions for different centralities are scaled by factors of ten. Dashed lines represent the exponential fits to the distributions and the dotted lines are Levy function fits. Error bars represent statistical errors only.

Each p_T spectrum in Fig. 2 has been fitted using both an exponential function (dashed lines) in m_T and a Levy function (dotted lines) which has an exponential-like shape at low p_T and is power-law-like at higher p_T. While the central data are fitted equally well by both functions the more peripheral spectra are better fitted by the Levy function indicating less thermal contributions in peripheral collisions.

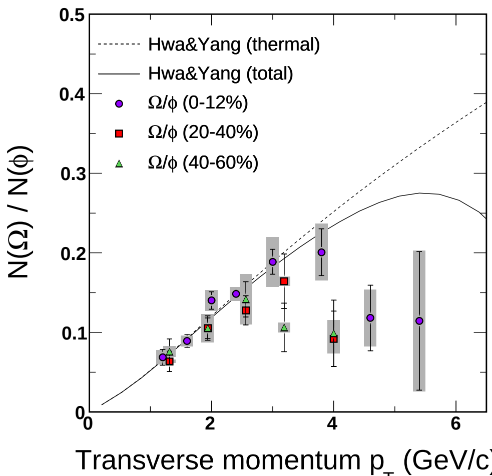

FIG. 3: (color online) The $N(\Omega)/N(\phi)$ ratio vs. p_T for three centrality bins in $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions. The solid and dashed lines represent recombination model predictions for central collisions [21] for total and thermal contributions, respectively.

In Fig. 3, the ratios of $N(\Omega)/N(\phi)$ vs. p_T are presented as a function of centrality. The Ω datapoints are from ref. [29] (for 0-10%) and ref. [30] for the other centralities. The errors of the ratios are dominated by the Ω datapoints. Also shown in the figure are recombination model expectations for central collisions [21] based on ϕ and Ω production from coalescence of thermal s quarks in the medium. The model describes the trend of the data up to $p_T \sim 4$ GeV/c but fails at higher p_T. Other models based on dynamical recombination of quarks [19, 31] were also compared to the data. However, ref. [19] overpredicts the ratio while ref. [31] gives the wrong shape. With decreasing centrality, the observed $N(\Omega)/N(\phi)$ ratios seem to turn over at successively lower values of p_T indicating a smaller contribution from thermal quark coalescence in more peripheral collisions. This is also reflected in the smooth evolution of the spectra shapes from the thermal-like exponential to power-law shapes shown in Fig. 2.

The nuclear modification factor $R_{CP}(p_T)$ measures the change of p_T distributions from peripheral to central collisions and has been measured for most of the identified hadrons. In Fig. 4, the high statistics ϕ-meson R_{CP} (solid circles) is compared to K^0_S (open triangles) and Λ (open squares) from ref. [11] for two different centrality combinations (upper and lower panels). In both panels the binary-scaled yield of ϕ-mesons is suppressed (R_{CP} below unity) in central compared to peripheral collisions. It has been shown that u, d and s quarks are approaching equilibration at hadronization [29]. The ϕ-meson R_{CP} is more consistent with that of K^0_S (meson) than of Λ (baryon) for the 0-5%/40-60% case (upper panel). This is as predicted by particle production models based on recombination of thermal quarks [19]. For the more peripheral bin (lower panel) the ϕ R_{CP} falls between that of the Λ and K^0_S.

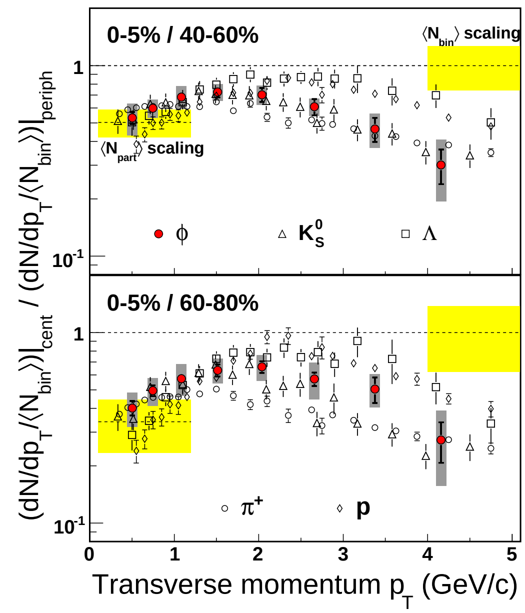

FIG. 4: (color online) The R_{CP} of mid-rapidity ϕ-mesons produced in $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions: (top) 0-5% vs. 40-60% and (bottom) 0-5% vs. 60-80% The shaded bands represent the uncertainties in the Glauber model calculations for $\langle N_{bin}\rangle$ and $\langle N_{part}\rangle$ [32]. Also shown are results for Λ and K^0_S [11] and protons and π^+ [33].

In the 60-80% centrality bin (see lower, binary collision-scaled ϕ production is very similar to that in p+p and d+Au collisions where strangeness production is canonically suppressed [34]. Therefore a baryon-meson scaling behaviour of R_{CP} is not expected in the lower panel of Fig. 4. In addition, for baryons and mesons respectively, there seems to be an ordering in terms of strangeness content. This has also been observed in R_{AA} for strange particles [35].

In summary, we have presented first measurements of the elliptic flow of ϕ-mesons as a function of collision centrality in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. At low p_T ($<$ 2 GeV/c), v_2 is consistent with hydrodynamical expectations. At intermediate p_T ($2 < p_T < 5$ GeV/c), v_2 of ϕ-mesons is consistent with number-of-quark scaling for mesons. These observations indicate the development of partonic collectivity in the medium. Measurements of the ϕ p_T spectra as a function of centrality show an evolution of the spectral shape from exponential to power-law-like with decreasing centrality, reflecting the increasing contributions from hard and possibly other non-equilibrium processes in more peripheral collisions. The result of a recombination model [21] is consistent with the trend of the central $N(\Omega)/N(\phi)$ ratio up to $p_T \sim 4$ GeV/c which covers more than 95% of the hadron yields. At higher p_T, the model fails. The ϕ-meson R_{CP} resembles the K^0_S for the 0-5%/40-60% case which is consistent with meson scaling. Since ϕ-mesons are made via coalescence of seemingly thermalized s quarks in central Au+Au collisions, the observations imply hot and dense matter with partonic collectivity has been formed at RHIC.

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[1] F. Karsch, Nucl. Phys. A **783** (2007) 13.
[2] Z. Fodor and S.D. Katz, Phys. Lett. B **534** (2002) 87.
[3] J. Phys. G: Nucl. Part. Phys. **30** (2004) S633 and Nucl. Phys. A **774** (2006) 1c.
[4] A. Shor, Phys. Rev. Lett. **54** (1985) 1122.
[5] T. Ishikawa *et al.*, Phys. Lett. B **608** (2005) 215.
[6] A. Sibirtsev, H.-W. Hammer, U.-G. Meissner, A.W. Thomas, Eur. Phys. J. **A29** (2006) 209.
[7] J. Adams *et al.*, Phys. Lett. B **612** (2005) 181.
[8] J.-Y. Ollitrault, Phys. Rev. D **46** (1992) 229.
[9] H. Sorge, Phys. Rev. Lett. **82** (1999) 2048.
[10] J. Adams *et al.*, Phys. Rev. Lett. **95** (2005) 122301 and references therein.
[11] J. Adams *et al.*, Phys. Rev. Lett. **92** (2004) 052302.
[12] P. Huovinen, P.F. Kolb, U. Heinz, P.V. Ruuskanen, and S.A. Voloshin, Phys. Lett. B **503** (2001) 58.
[13] C. Nonaka *et al.*, Phys. Lett. B **583** (2004) 73.
[14] T. Hirano and Y. Nara, Phys. Rev. C **69** (2004) 034908.
[15] S.S. Adler *et al.*, Phys. Rev. Lett. **91** (2003) 182301.
[16] J. Adams *et al.*, Phys. Rev. C **71** (2005) 064902.
[17] S. A. Voloshin, Nucl.Phys. A **715** (2003) 379c.
[18] D. Molnar and S.A. Voloshin, Phys. Rev. Lett. **91** (2003) 092301.
[19] R. J. Fries *et al.*, Phys. Rev. C **68** (2003) 044902.
[20] J.H. Chen *et al.*, Phys. Rev. C **74** (2006) 064902.
[21] R. Hwa and C.-B. Yang, *nucl-th/0602024*.
[22] K.H. Ackermann *et al.*, Nucl. Intr. Meth. in Phys. Res. A **499** (2003) 624.
[23] Review of Particle Physics, J. Phys. G: Nucl. Part. Phys. **33** (2006) 1.
[24] N. Borghini and J.-Y. Ollitrault, Phys. Rev. C **70** (2004) 064905.
[25] A.M. Poskanzer and S.A. Voloshin, Phys. Rev. C **58** (1998) 1671.
[26] C. Adler *et al.*, Phys. Rev. C **66** (2002) 034904.
[27] J. Adams *et al.*, Phys. Rev. C **72** (2005) 014904.
[28] X. Dong *et al.*, Phys. Lett. B **597** (2004) 328.
[29] J. Adams *et al.*, Nucl. Phys. A **757** (2005) 102.
[30] J. Adams *et al.*, *nucl-ex/0606014*.
[31] L.-W. Chen and C.M. Ko, Phys. Rev. C 73 (2006) 044903.
[32] J. Adams *et al.*, Phys. Rev. C **70** (2004) 054907.
[33] B.I. Abelev *et al.*, Phys. Rev. Lett. **97** (2006) 152301.
[34] A. Tounsi, A. Mischke, and K. Redlich, Nucl. Phys. A **715** (2003) 565c.
[35] S. Salur, (STAR Collaboration), Nucl. Phys. A **774** (2006) 657c.